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# Improved Measurement of $CP$ Asymmetries in $B^0 \to (c\bar{c})K^{0(*)}$ Decays

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We present results on time-dependent *CP* asymmetries in neutral $B$ decays to several *CP* eigenstates. The measurements use a data sample of about $227 \times 10^6$ $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected by the *BABAR* detector at the PEP-II asymmetric-energy $B$ Factory at SLAC. The amplitude of the *CP* asymmetry, $\sin 2\beta$ in the Standard Model, is derived from decay-time distributions from events in which one neutral $B$ meson is fully reconstructed in a final state containing a charmonium meson and the other $B$ meson is determined to be either a $B^0$ or $\overline{B}^0$ from its decay products. We measure $\sin 2\beta = 0.722 \pm 0.040(\text{stat}) \pm 0.023(\text{syst})$ in agreement with the Standard Model expectation.

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Charge-parity (*CP*) violation in the $B$ meson system has been established by the *BABAR* [1] and Belle [2] collaborations. The Standard Model of electroweak interactions describes *CP* violation as a consequence of an irreducible phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [3]. In this framework, measurements of *CP* asymmetries in the proper-time distribution of neutral $B$ decays to *CP* eigenstates containing a charmonium and $K^0$ meson provide a direct measurement of $\sin 2\beta$ [4]. The angle $\beta$ is $\arg\left[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*\right]$, where $V_{ij}$ are CKM matrix elements.

In this Letter we report on an updated measurement of $\sin 2\beta$ in $(227 \pm 2) \times 10^6$ $B\overline{B}$ decays using $B^0$ decays to the final states $J/\psi K^0_S$, $J/\psi K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, and $J/\psi K^{*0}(K^{*0} \rightarrow K^0_S\pi^0)$ [5]. The *BABAR* detector and the measurement technique are described in detail in Refs. [6] and [7], respectively. Changes in the analysis with respect to the previously published result include $140 \times 10^6$ more $B\overline{B}$ events, an improved event reconstruction applied to all of the data, a new flavor-tagging algorithm, and fewer assumptions about the *CP* properties of background events.

The proper-time distribution of $B$ meson decays to a *CP* eigenstate $f$ can be expressed in terms of a complex parameter $\lambda$ [8], which depends on both the $B^0$-$\overline{B}^0$ oscillation amplitude and the decay amplitudes for $\overline{B}^0 \rightarrow f$ and $B^0 \rightarrow f$. The decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the other $B$ meson $B_{\rm tag}$ decays as a $B^0$ ($\overline{B}^0$) is given by

$$\mathrm{f}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 \pm \frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2} \sin(\Delta m_d \Delta t) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m_d \Delta t) \right], \quad (1)$$

for a $B$ from a $\Upsilon(4S) \rightarrow B^0\overline{B}^0$ decay, where $\Delta t$ is the difference between the proper decay times of the reconstructed $B$ meson $B_{\rm rec}$ and $B_{\rm tag}$, $\tau_{B^0}$ is the $B^0$ lifetime, and $\Delta m_d$ is the $B^0$-$\overline{B}^0$ oscillation frequency. The decay width difference $\Delta\Gamma$ between the $B^0$ mass eigenstates is assumed to be zero. The sine term is due to the interference between direct decay and decay after a net $B^0$-$\overline{B}^0$ oscillation. A non-zero cosine term arises from the interference between decay amplitudes with different weak and strong phases (direct *CP* violation) or from *CP* violation in $B^0$-$\overline{B}^0$ mixing.

In the Standard Model, *CP* violation in mixing is negligible, as is direct *CP* violation for $b \rightarrow c\overline{c}s$ decays that contain a charmonium meson [8]. With these assumptions $\lambda = \eta_f e^{-2i\beta}$, where $\eta_f$ is the *CP* eigenvalue of final state $f$. Thus, the time-dependent *CP* asymmetry is

$$A_{CP}(\Delta t) \equiv \frac{\mathrm{f}_+ - \mathrm{f}_-}{\mathrm{f}_+ + \mathrm{f}_-} = -\eta_f \,\sin 2\beta\, \sin(\Delta m_d\, \Delta t), \quad (2)$$

with $\eta_f = -1$ for $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, and $+1$ for $J/\psi K^0_L$. Due to the presence of even ($L$=0, 2) and odd ($L$=1) orbital angular momenta in the $B \rightarrow J/\psi K^{*0}$ final state, there can be *CP*-even and *CP*-odd contributions to the decay rate. When the angular information in the decay is ignored, the measured *CP* asymmetry in $J/\psi K^{*0}$ is reduced by a factor $|1-2R_\perp|$, where $R_\perp$ is the fraction of the $L$=1 contribution. We have measured $R_\perp = 0.230 \pm 0.015 \pm 0.004$ [9], which gives an effective $\eta_f = 0.51 \pm 0.04$, after acceptance corrections.

In addition to the *CP* modes described above, we utilize a large sample ($B_{\rm flav}$) of $B^0$ decays to the flavor eigenstates $D^{(*)-}h^+(h^+ = \pi^+, \rho^+$, and $a_1^+)$ and $J/\psi K^{*0}(K^{*0} \rightarrow K^+\pi^-)$ for calibrating our flavor tagging and $\Delta t$ resolution. Validation studies are performed with a control sample of $B^+$ mesons decaying to the final states $J/\psi K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$, and $\eta_c K^+$. The event selection and candidate reconstruction are unchanged from those described in Refs. [1, 7, 10], except that only the $\eta_c \rightarrow K^0_S K^+\pi^-$ channel is used in the $B^0 \rightarrow \eta_c K^0_S$ and $B^\pm \rightarrow \eta_c K^\pm$ modes ($2.91 < m_{K^0_S K^+\pi^-} < 3.05\,\mathrm{GeV}/c^2$).

The time interval $\Delta t$ between the two $B$ decays is calculated from the measured separation $\Delta z$ between the decay vertices of $B_{\rm rec}$ and $B_{\rm tag}$ along the collision ($z$) axis [7]. We find the $z$ position of the $B_{\rm rec}$ vertex from its charged tracks. The $B_{\rm tag}$ decay vertex is determined by fitting tracks not belonging to the $B_{\rm rec}$ candidate to a common vertex, employing constraints from the beam spot location and the $B_{\rm rec}$ momentum [7]. We accept events with a calculated $\Delta t$ uncertainty of less than 2.5 ps and $|\Delta t| < 20$ ps. The fraction of events satisfying these requirements is 95%. The r.m.s. $\Delta t$ resolution is 1.1 ps for the 99.7% of these events that exclude outliers.

We use multivariate algorithms to identify signatures of $B$ decays that determine ("tag") the flavor at decay of the $B_{\rm tag}$ to be either a $B^0$ or $\overline{B}^0$. Primary leptons from semileptonic $B$ decays are selected from identified elec-

TABLE I: Efficiencies $\epsilon_i$, average mistag fractions $w_i$, mistag fraction differences $\Delta w_i \equiv w_i(B^0) - w_i(\overline{B}^0)$, and $Q$ extracted for each tagging category $i$ from the $B_{\rm flav}$ sample.

| Category | $\varepsilon$ (%) | $w$ (%) | $\Delta w$ (%) | $Q$ (%) |
|---|---|---|---|---|
| `Lepton` | $8.6 \pm 0.1$ | $3.2 \pm 0.4$ | $-0.2 \pm 0.8$ | $7.5 \pm 0.2$ |
| `Kaon I` | $10.9 \pm 0.1$ | $4.6 \pm 0.5$ | $-0.7 \pm 0.9$ | $9.0 \pm 0.2$ |
| `Kaon II` | $17.1 \pm 0.1$ | $15.6 \pm 0.5$ | $-0.7 \pm 0.8$ | $8.1 \pm 0.2$ |
| `Kaon-Pion` | $13.7 \pm 0.1$ | $23.7 \pm 0.6$ | $-0.4 \pm 1.0$ | $3.8 \pm 0.2$ |
| `Pion` | $14.5 \pm 0.1$ | $33.0 \pm 0.6$ | $5.1 \pm 1.0$ | $1.7 \pm 0.1$ |
| `Other` | $10.0 \pm 0.1$ | $41.1 \pm 0.8$ | $2.4 \pm 1.2$ | $0.3 \pm 0.1$ |
| All | $74.9 \pm 0.2$ | | | $30.5 \pm 0.4$ |

trons and muons as well as isolated energetic tracks. The charges of identified kaon candidates define a kaon tag. Soft pions from $D^{*+}$ decays are selected on the basis of their momentum and direction with respect to the thrust axis of $B_{\rm tag}$. These algorithms are combined to account for correlations among different sources of flavor information and to provide an estimate of the mistag probability for each event. These algorithms have been improved relative to Ref. [1] with the addition of information from low-momentum electrons, $\Lambda \to p\pi$ decays, and additional correlations among identified kaon candidates.

Each event is assigned to one of six tagging categories if the estimated mistag probability is less than 45%. The `Lepton` category contains events with an identified lepton; the remaining events are divided into the `Kaon I`, `Kaon II`, `Kaon-Pion`, `Pion`, or `Other` categories based on the estimated mistag probability. This new definition of tagging categories improves the overall performance of the tagging algorithm, while largely preserving the separation of events with differing sources of tagging information. For each category $(i)$, the tagging efficiency $\varepsilon_i$ and fraction $w_i$ of events having the wrong tag assignment are measured from data (Table I). The effective tagging efficiency $Q \equiv \sum_i \varepsilon_i(1-2w_i)^2$ improves by about 5% (relative) over the algorithm used in Ref. [1]. In addition, the correlations among the mistag parameters and those of the $\Delta t$ resolution function are reduced.

The beam-energy substituted mass $m_{\rm ES} = \sqrt{(E^{\rm cm}_{\rm beam})^2 - (p^{\rm cm}_B)^2}$ (all modes except for $J/\psi K^0_L$) or the difference $\Delta E$ between the candidate center-of-mass energy and $E^{\rm cm}_{\rm beam}$ ($J/\psi K^0_L$ channel) are used to determine the composition of our final sample (Fig. 1). Here, $E^{\rm cm}_{\rm beam}$ and $p^{\rm cm}_B$ are the beam energy and $B$ momentum in the center-of-mass frame. Events with $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$ ($\Delta E < 80\,{\rm MeV}$) are used so that the properties of the background contributions can be measured. The more restricted signal region (Table II) contains 7730 *CP* candidate events that satisfy the tagging and vertexing requirements.

For all modes except $\eta_c K^0_S$ and $J/\psi K^0_L$ we use simulated events to estimate the fractions of events that peak in the $m_{\rm ES}$ signal region due to cross-feed from other decay modes (peaking background). For the $\eta_c K^0_S$ mode the cross-feed fraction is determined from a fit to the $M_{KK\pi}$ and $m_{\rm ES}$ distributions in data. For the $J/\psi K^0_L$ decay mode, the composition, effective $\eta_f$, and $\Delta E$ distribution of the individual background sources are determined either from simulation (for $B \to J/\psi X$) or from the $m_{\ell^+\ell^-}$ sidebands in data (for fake $J/\psi \to \ell^+\ell^-$).

We determine sin$2\beta$ with a simultaneous maximum likelihood fit to the $\Delta t$ distributions of the tagged $B_{CP}$ and $B_{\rm flav}$ samples. The $\Delta t$ distributions of the $B_{CP}$ sample are modeled by Eq. 1 with $|\lambda| = 1$. Those of the $B_{\rm flav}$ sample evolve according to the known frequency for flavor oscillation in $B^0$ mesons. The observed amplitudes for the *CP* asymmetry in the $B_{CP}$ sample and for flavor oscillation in the $B_{\rm flav}$ sample are assumed to be reduced by the same factor $1-2w$ due to flavor mistags. The $\Delta t$ distributions for the signal are convolved with a common resolution function, modeled by the sum of three Gaussians [7]. Backgrounds are incorporated with an empirical description of their $\Delta t$ spectra, containing prompt and non-prompt components convolved with a resolution function [7] distinct from that of the signal.

There are 65 free parameters in the fit: sin$2\beta$ (1), the average mistag fractions $w$ and the differences $\Delta w$ between $B^0$ and $\overline{B}^0$ mistag fractions for each tagging category (12), parameters for the signal $\Delta t$ resolution (7), parameters for *CP* background time dependence (8), and the difference between $B^0$ and $\overline{B}^0$ reconstruction and tag-

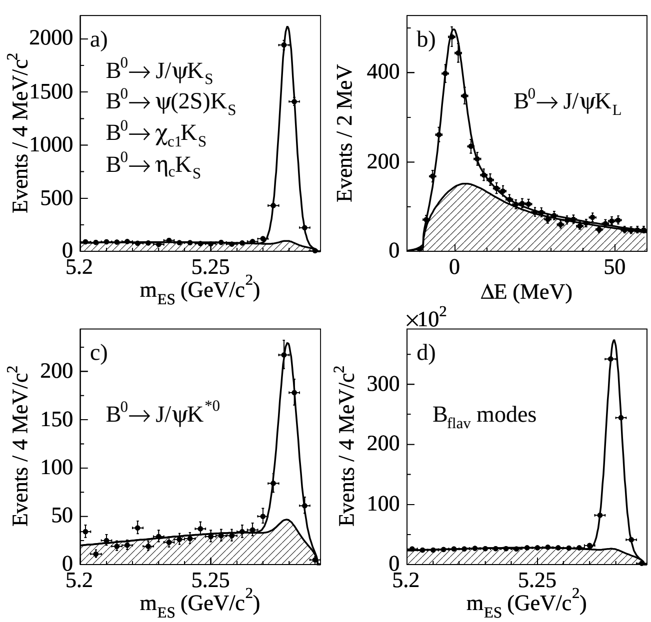


FIG. 1: Distributions for $B_{CP}$ and $B_{\rm flav}$ candidates satisfying the tagging and vertexing requirements: a) $m_{\rm ES}$ for the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, b) $\Delta E$ for the final state $J/\psi K^0_L$, c) $m_{\rm ES}$ for $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$, and d) $m_{\rm ES}$ for the $B_{\rm flav}$ sample. In each plot, the shaded region is the estimated background contribution.

TABLE II: Number of events $N_{\rm tag}$ in the signal region after tagging and vertexing requirements, signal purity $P$ including the contribution from peaking background, and results of fitting for $CP$ asymmetries in the $B_{CP}$ sample and various subsamples. In addition, results on the $B_{\rm flav}$ and charged $B$ control samples test that no artificial $CP$ asymetry is found where we expect no $CP$ violation ($\sin2\beta = 0$). Errors are statistical only. The signal region is $5.27 < m_{\rm ES} < 5.29\,{\rm GeV}/c^2$ ($|\Delta E| < 10\,{\rm MeV}$ for $J/\psi\,K^0_L$).

| Sample | $N_{\rm tag}$ | $P(\%)$ | $\sin2\beta$ |
|---|---|---|---|
| Full $CP$ sample | 7730 | 76 | $0.722 \pm 0.040$ |
| $J/\psi\,K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$,$\eta_c K^0_S$ | 4370 | 90 | $0.75 \pm 0.04$ |
| $J/\psi\,K^0_L$ | 2788 | 56 | $0.57 \pm 0.09$ |
| $J/\psi\,K^{*0}(K^{*0} \rightarrow K^0_S\pi^0)$ | 572 | 68 | $0.96 \pm 0.32$ |
| 1999-2002 data | 3032 | 77 | $0.74 \pm 0.06$ |
| 2003-2004 data | 4698 | 77 | $0.71 \pm 0.05$ |
| $J/\psi\,K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ only ($\eta_f = -1$) | | | |
| $J/\psi\,K^0_S$ ($K^0_S \rightarrow \pi^+\pi^-$) | 2751 | 96 | $0.79 \pm 0.05$ |
| $J/\psi\,K^0_S$ ($K^0_S \rightarrow \pi^0\pi^0$) | 653 | 88 | $0.65 \pm 0.12$ |
| $\psi(2S)K^0_S$ ($K^0_S \rightarrow \pi^+\pi^-$) | 485 | 82 | $0.88 \pm 0.14$ |
| $\chi_{c1}K^0_S$ | 194 | 81 | $0.69 \pm 0.23$ |
| $\eta_c K^0_S$ | 287 | 64 | $0.17 \pm 0.25$ |
| `Lepton` category | 490 | 96 | $0.75 \pm 0.08$ |
| `Kaon I` category | 648 | 93 | $0.75 \pm 0.08$ |
| `Kaon II` category | 1021 | 89 | $0.77 \pm 0.09$ |
| `Kaon-Pion` category | 769 | 90 | $0.77 \pm 0.15$ |
| `Pion` category | 835 | 87 | $0.96 \pm 0.22$ |
| `Other` category | 607 | 88 | $0.23 \pm 0.51$ |
| $B_{\rm flav}$ sample | 72878 | 85 | $0.021 \pm 0.013$ |
| $B^+$ sample | 18294 | 88 | $0.003 \pm 0.020$ |

ging efficiencies (7); for $B_{\rm flav}$ background, time dependence (3), $\Delta t$ resolution (3), and mistag fractions (24). For the $CP$ modes (except for $J/\psi\,K^0_L$), the apparent $CP$ asymmetry of the non-peaking background in each tagging category is allowed to float. This asymmetry is parameterized so that it does not depend on the value of $\sin2\beta$.

We fix $\tau_{B^0} = 1.536\,{\rm ps}$, $\Delta m_d = 0.502\,{\rm ps}^{-1}$ [11], $|\lambda| = 1$, and $\Delta\Gamma = 0$. The determination of the mistag fractions and $\Delta t$ resolution function parameters for the signal is dominated by the high-statistics $B_{\rm flav}$ sample. Background parameters are determined mainly from events with $m_{\rm ES} < 5.27\,{\rm GeV}/c^2$.

The fit to the $B_{CP}$ and $B_{\rm flav}$ samples yields

$$\sin2\beta = 0.722 \pm 0.040({\rm stat}) \pm 0.023({\rm syst}).$$

Figure 2 shows the $\Delta t$ distributions and asymmetries in yields between $B^0$ tags and $\overline{B}{}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of $\Delta t$, overlaid with the projection of the likelihood fit result.

In a separate fit with only the high purity $\eta_f = -1$ sample, we obtain $|\lambda| = 0.950 \pm 0.031({\rm stat}) \pm 0.013({\rm syst})$. The correlation between the coefficients multiplying the $\sin(\Delta m_d\Delta t)$ and $\cos(\Delta m_d\Delta t)$ terms in Eq. 1 is $-2\%$.

The sources of systematic error are summarized in Table III. These include the uncertainties in the level and $CP$ asymmetry of the peaking background, the assumed parameterization of the $\Delta t$ resolution function, possible differences between the $B_{\rm flav}$ and $B_{CP}$ mistag fractions, knowledge of the event-by-event beam spot position, and the possible interference between the suppressed $\bar{b} \rightarrow \bar{u}c\bar{d}$ amplitude with the favored $b \rightarrow c\bar{u}d$ amplitude for some tag-side $B$ decays [12]. In addition, we include the variation due to the assumed values of $|\lambda|$ and $\Delta\Gamma$. We assign the change in the measured $\sin2\beta$ when we float $|\lambda|$ and when we set $\Delta\Gamma/\Gamma = \pm0.02$, the latter being considerably larger than recent Standard Model estimates [13]. The total systematic error on $\sin2\beta$ ($|\lambda|$) is 0.023 (0.013).

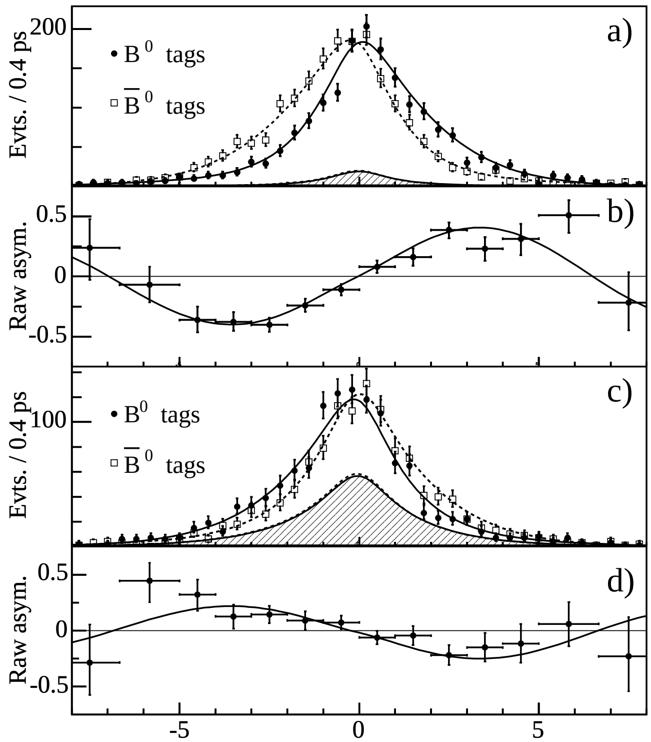


FIG. 2: a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$) in the signal region with a $B^0$ tag $N_{B^0}$ and with a $\overline{B}{}^0$ tag $N_{\overline{B}{}^0}$, and b) the raw asymmetry $(N_{B^0} - N_{\overline{B}{}^0})/(N_{B^0} + N_{\overline{B}{}^0})$, as functions of $\Delta t$. Figs. c) and d) are the corresponding plots for the $\eta_f = +1$ mode $J/\psi K^0_L$. All plots exclude `Other`- tagged events. The solid (dashed) curves represent the fit projections in $\Delta t$ for $B^0$ ($\overline{B}{}^0$) tags. The shaded regions represent the estimated background contributions.

The large $B_{CP}$ sample allows a number of consistency checks, including separation of the data by decay mode and tagging category, as shown in Table II. Considering statistical errors only, the probability of finding a worse agreement in measured $\sin2\beta$ values across decay modes is 7% and between tagging categories is 86%. The results of fits to the control samples of non-$CP$ decay modes

TABLE III: Sources of systematic error on $\sin 2\beta$ and $|\lambda|$.

| Source | $\sigma(\sin 2\beta)$ | $\sigma(\|\lambda\|)$ |
|---|---|---|
| *CP* backgrounds | 0.012 | 0.002 |
| $\Delta t$ resolution function | 0.011 | 0.003 |
| $J/\psi K_L^0$ backgrounds | 0.011 | N/A |
| Mistag fraction differences | 0.007 | 0.001 |
| Beam spot | 0.007 | 0.001 |
| $\Delta m_d$, $\tau_B$, $\Delta\Gamma/\Gamma$, $\|\lambda\|$ | 0.005 | 0.001 |
| Tag-side interference | 0.003 | 0.012 |
| MC statistics | 0.003 | 0.003 |
| Total systematic error | 0.023 | 0.013 |

indicate no statistically significant asymmetry.

This measurement of $\sin 2\beta$ supersedes our previous result [1] and is consistent with the range implied by other measurements and theoretical estimates of the magnitudes of CKM matrix elements in the context of the Standard Model [14]. The theoretical uncertainty on the interpretation of the measurement of $\sin 2\beta$ in these modes is approximately 0.01 [8]. As the current measurement is statistics limited, future measurements will add further model-independent constraints on the position of the apex of the unitarity triangle [14]. We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

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